AIAA 2002-0624

Future Directions in Spacecraft Charging-2001 and Beyond

H. B. Garrett
The Jet Propulsion Laboratory
4800 Oak Grove Dr.
Pasadena, CA 91109

40th AIAA Aerospace Sciences Meeting & Exhibit
14-17 January 2002 / Reno, NV

For permission to copy or republish, contact the copyright owner named on the first page. For AIAA-held copyright, write to AIAA, Permissions Department, 1801 Alexander Bell Drive, Suite 500, Reston, VA 20191-4344.

AIAA-2002-0624

FUTURE DIRECTIONS IN SPACECRAFT CHARGING-2001 AND BEYOND

H. Garrett
The Jet Propulsion Laboratory
4800 Oak Grove Dr.
Pasadena, CA, 91109

Abstract

Spacecraft charging and its effects on spacecraft are an accepted fact in the spacecraft design community. From missions such as SCATHA and CRRES that specifically studied surface and internal charging to well-documented charging events on various DoD, NASA, and commercial spacecraft, spacecraft charging has been demonstrated to cause deleterious effects on operations in space. While previous papers and talks have concentrated on documenting these effects and providing methods for limiting their more severe consequences, this talk will discuss possible future directions that the field may take and offer hints at potential new mitigation methods. Specific concerns are the surface charging interactions with truly large spacecraft such as the proposed Solar Sails or Gossamer structures that are being considered for NASA's more advanced missions. In addition, environments such as found at Jupiter in and near Europa or Io pose unique internal charging environments. Taken together, these possible new directions in space systems and missions represent exciting opportunities for the spacecraft engineering community.

I. Introduction

Consider the current state of the field of spacecraft charging. Spacecraft charging is still a growing, vibrant field as evidenced by several recent conferences[1,2], reviews[3,4], and books[5-7] on the generic issues associated with plasma interactions or specific areas such as surface charging. Still, as Koons et al.[8] demonstrated, charging (or perhaps more properly differential charging followed by discharging) effects are still a major source of spacecraft anomalies[9,10]. Whether it be surface charging, internal charging, plasma interactions at low altitudes, or induced fields on tethers, the buildup of charge on or in spacecraft pose a continuing design problem for the spacecraft builder.

Undoubtedly, the largest change since 1980 has been in emphasis as there has been a major shift in attitude vis a vis surface charging versus internal charging caused by penetrating electrons. While the former continues to be an important process, in recent years it has become increasingly clear that, as external charging and the elimination of differential potentials are routinely addressed in spacecraft design, a growing proportion of spacecraft anomalies are now believed to be caused by "internal" charging (defined as charging not on the external visible surface of the spacecraft, but by charging that causes discharges near internal electronics). To address this issue, a new NASA Handbook, "Avoiding Problems Caused by Spacecraft On-Orbit Internal Charging Effects"[11] has been written. Likewise, with the importance of the International Space Station to the national space program, charging effects unique to the low Earth orbit have become of increasing concern. Finally, the continuing desire to use high voltages in space (especially for solar arrays) and to utilize tethers have in particular led to growth in these areas in recent years.

"Copyright © 2002 by the American Institute of Aeronautics and Astronautics, Inc. The U.S. Government has a royalty-free license to exercise all rights under the copyright claimed herein for Governmental purposes. All other rights are reserved by the copyright owner."

II. Surface Charging

Surface charging in this paper refers to charging and electrostatic discharge effects on the outside of the spacecraft (generally the visible surface materials). It is now universally recognized as an important design consideration for spacecraft in Earth orbit, particularly at geosynchronous orbit where potentials can reach ~18 kV. Of increasing interest, however, is the portion of the charging environment below 1000 km in the polar regions. Although not as dramatic as geosynchronous charging, "low altitude" surface charging in this region is more common than originally thought (see Section IV and review by Hastings[3]). In the future, surface charging outside Earth's environment will also be of concern. In particular, the spacecraft surface charging environment has been mapped out for other planets--surface potentials have been estimated for Jupiter and Saturn[12,13]. In support of such estimates, the Voyager spacecraft may have observed large surface charging throughout the solar system--possibly tens of kV at

Jupiter[14] and -400 V at Uranus[15]. Many interplanetary spacecraft are now, as a result, designed to minimize surface charging as a matter of course. These design techniques are based on design guidelines and standards defined in NASA 2361[16] and MIL-STD 1541A[17]. The methods for controlling and mitigating surface charging were the direct outgrowth of the SCATHA experience[18-20]. Actual flight experience over the last decade has repeatedly demonstrated the value of these methods. Indeed they have consistently proven to be successful in limiting the effects of surface charging whether that be near the Earth or a more exotic space environment.

Although it is still difficult to adequately predict geomagnetic "weather" in terms of substorms with anything more than a half to one hour lead time[21-23], it has proven possible to estimate absolute surface charging levels at a given satellite location with some accuracy from geomagnetic indices[24,25] or, better still, in-situ measurements of the plasma (note: differential charging is another matter altogether and requires intimate knowledge of the spacecraft design and sophisticated codes such as NASCAP[26] to provide accurate estimates). In Garrett et al.[27], data from plasma sensors on one geosynchronous spacecraft were successfully used to estimate charging levels at another spacecraft. These measurements, obtainable in near-real time, clearly demonstrate that charging levels at other spacecraft can be estimated within several hours of local time around an observing spacecraft. Indeed, data from one spacecraft[27] (the USAF Defense Support Program or DSP satellite) were used to estimate the charging environment on the near-by ATS-6. Of interest is that this was done with only three electron energy channels between 30 and 95 keV. The results also demonstrated that surface charging is primarily a function of the electron current at energies of a few 10's of keV and that it is possible to provide a "spacecraft surface charging index". Hopefully the future will see the development of this index into a useful method of assisting in the mitigation of spacecraft anomalies at geosynchronous orbit.

Despite these advances, surface charging at geosynchronous orbit can still pose a threat to spacecraft survivability[8,28-30]. Recently, new evidence for the complexities associated with the surface charging/arcing process has emerged in the form of catastrophic, continuous arcs between adjacent solar cells on two high-powered spacecraft operating in geosynchronous orbit[31]. Ground experiments and theory have shown that most probable location for electrical discharges to occur on the surfaces of high voltage solar arrays is at the so-called triple junction: the interface between a metallic interconnect, coverglass, and plasma[32-34]. Although this type of arc is not believed to be able to cause substantial damage to a solar array, it has been hypothesized and demonstrated in the laboratory that such an arc can generate sufficient local heating to initiate outgassing and polymer pyrolysis[34,35]. This in turn can generate enough gas and plasma between biased solar cells to trigger long duration arcs that can be maintained by the solar array and cause serious damage to an array. Fortunately, mitigation techniques[34,35] (e.g., limiting the potential between adjacent solar cells and insulating the region between likely breakdown sites) have proven in testing to be very effective at reducing this problem. The lesson for the future, however, is that, as our systems evolve, spacecraft charging can strike in unanticipated ways—"eternal vigilance" may be the watchword for the charging community.

III. Internal Charging

Internal charging as used here refers to the accumulation of electrical charge on interior ungrounded metals or on or in dielectrics inside a spacecraft. The key difference between "internal" and external/surface charging is that surface electrostatic discharges often are loosely coupled to victim circuits, whereas internal discharges may occur directly adjacent to victim circuits. If Faraday cage construction is employed, ESD events outside the Faraday cage, even if under thermal blankets, could be called "external" in this context. Electrons with 500 keV of energy or more are considered to be the primary environment responsible for internal charging problems as they can easily penetrate the standard Faraday cage shielding. Although the fluxes are lower at these higher energies, any internal electrostatic discharge (ESD) spark they might cause is closer to victim electronics than external ESDs and therefore can cause significant upset or damage to satellite electronics. Note, however, that "internal" charging as defined herein can occur under thinner protective layers (as thin as a thermal blanket) and the energy threshold for internal charging can be caused by electron environments of energies perhaps as low as 100 keV. The key is the deposition rate/fluence after the shielding effects (as described later in this section).

Internal charging may actually be more severe outside Earth orbit--during the Voyager 1 passage by Jupiter on September 5, 1977[36,37], 42 identical electrical anomalies were observed. These were subsequently attributed to internal charging. In particular, it was postulated that ~MeV electrons had penetrated the surface of a cable and built up charge sufficient to cause arcing. For Earth orbit, the presence of internal charging continues to be investigated and reported[38-41].

As to the future, our understanding of how the internal discharge process is initiated is only now beginning to yield to experimental study. Consider cable insulation charging. Frederickson[42] has made great strides in testing specific configurations. He has found[43] that the threat starts with charging in the dielectric (so that thinner wire insulation is better) and the threat is enhanced by small plasma plumes drifting onto victim areas (such as exposed high voltage terminals), so keeping the wire bundle tightly bound is better. This research promises to change the way we think about internal charging and may lead to significant improvements in its mitigation. Even so, the problem of internal charging will be getting worse in the future rather than better. Although the environment is not changing , economics is forcing less and less shielding, lighter weight structural materials, and even elimination of Faraday cage construction. At the same time the devices (integrated circuits) are going to smaller scale sizes and thus are more susceptible to damage. As pointed out by Frederickson, the designer has an even greater challenge ahead; design rules that may have worked yesterday will need re-evaluation with changed parts and structural design. Fortunately, as in the case of surface charging, there are currently on station several geosynchronous monitors that can be used to provide a real-time "internal charging index". The GOES series of spacecraft, for example, provide a real time estimate of the high energy electron environment. Thus, when the flux they measure exceeds a critical number for a given spacecraft, arcing may occur. Future missions may be able to use this information to limit the effects of arcing on internal surfaces.

IV. Low Altitude Charging

Spacecraft orbiting at low altitudes must also be concerned with charging. Because of the complex effects of structure size and shape on the magnetohydrodynamic flow fields of high density plasmas, hypersonic plasma interactions at low altitudes have always presented an analytic challenge[44,45] Likewise, the desire to operate at increasingly higher voltages has greatly added to the computational difficulties associated with this problem. Fortunately, with the continuing growth in computer capability, a number of spacecraft charging problems at low altitudes are for the first time yielding to numerical analysis. Intricate geometries, magnetic fields, changing composition, and high, imposed potentials can now all be effectively modeled. Indeed, this conference has two sessions devoted to high voltage interactions with the Space Station. As these sessions testify and as detailed in Hastings' review[3], low altitude charging analysis is coming of age.

In addition to ongoing studies on the International Space Station, there is considerable experimental work related to this phenomenon (i.e., current collection by high voltages in a wake) that has been carried out in the laboratory[46] and in-situ by the Shuttle Charging Hazards and Wake Studies (CHAWS) experiment[47,48]. CHAWS consisted of plasma monitors and a bistable probe mounted on the Shuttle Wake Shield Facility (WSF). The experiment measured the plasma current in the wake of the WSF as functions of negative potential of the probe (up to -5000 V relative to the WSF). The experiment was modeled using the programs Potentials of Large Objects in the Auroral Region (POLAR)[49] and Dynamic Plasma Analysis Code (DynaPAC)[50]. The flight data and simulations indicated that the current collected had a power law dependence on the potential but a less than linear dependence on the plasma density. The measurements at low voltages, however, differed from the models as the latter predicted a threshold for current collection at -100 V which was not observed in the data[51].

The calculations just presented barely introduce the rich variety of low altitude plasma interactions now being studied. Consider the growing interest in electrodynamic tethers[52]. Multi-km long thin conducting cables are now possible and have indeed been demonstrated (e.g., the TSS-1 Shuttle experiment[53-55]). One interest here is the use of these tethers to generate electricity. For a conducting object in low Earth orbit, the vxB electric field varies from a low of about (0.1 V/m) at the equator to a maximum of (0.3 V/m) over the polar caps. For a 10 km tether (easily possible with present technology), a potential difference of up to 3,000 V is possible--a spacecraft can in principle draw power from this voltage drop but at the price of a loss in orbital altitude[56,57]. By biasing a tether, it can by used for spacecraft propulsion and orbit reboost[58-61] as in the case of the Plasma Motor Generator[62] or the proposed Propulsive Small Expendable Deployer System (ProSEDS) experiment[58]. Tethers have even been suggested as possible power sources for jovian missions[63]. At Jupiter, however, the plasma corotates faster than the orbital velocity so that a vehicle can gain orbital altitude using a tether. Problems for tethers arise, however, in achieving the current flow necessary to utilize the energy as it is not clear that a sufficient ion current is possible without resorting to a plasma emitter or similar emission device[3,64] to enhance positive ion current collection. Related issues are wave dissipation and radiation impedance associated with the passage of the tether[65-69]. Tethers are and will be an on-going topic of research and debate in the future.

Over the last decade, observations of surface charging on low Earth orbit, polar spacecraft have mainly been concerned with the Defense Meteorological Satellite Program (DMSP) satellites. Papers[70,71] have reported potentials ranging from a few hundreds of volts to over a kV. It now appears that far from being a very rare event, moderate charging events (i.e., above the ~400 V differential potentials normally believed to be the minimum necessary to cause surface arcing) are not uncommon for polar orbiting spacecraft. Discharge-induced anomalies, however, are believed to be rare. Recently, however, Anderson and Koons[72] have reported observing an operational anomaly on the DMSP F13 satellite--on May 5, 1995, the microwave imager experiment microprocessor locked-up. At the time of the event, the spacecraft frame potential was estimated at -460 V and surface potentials as high as -3 kV may have occurred in a ~6 s period. Cooke[73] used the POLAR code to simulate the charging of the DMSP satellite at the time of the event. His results indicate that the highest potentials are only achieved by a few surfaces that have ion collection limited by their locations perhaps explaining in part the rarity of such events (though surface material choices may be a more likely cause). Even so, given adequate measurements of ionospheric and geomagnetic activity, it should be possible to determine the occurrence of such events in real time as in the case of geosynchronous charging.

Another area of low altitude charging interest is that associated with induced potentials due to biased surfaces such as solar arrays. In addition to arcing, biased solar arrays at low altitude have been observed to drive plasma effects (e.g., broadband fluctuations extending beyond 1 MHz)[74]. In a series of rocket and satellite experiments, the DoD and NASA have completed several interesting studies over the last decade into the effects of induced high potentials on solar arrays and of plasma beams on spacecraft potentials. Intended primarily to parameterize the ranges over which exposed high potential surfaces can be biased before arcing sets in and to demonstrate control of the discharge process, two series of experiments stand out. The first of these are the solar array experiments associated with the PASP Plus APEX satellite experiment[75,76]. Launched into a 363 by 2550 km elliptical orbit on August 3, 1994 by a Pegasus rocket, this experiment consisted of a collection of several types of solar array cells. Ranging from solar concentrators to representative samples of the International Space Station arrays, the cells were biased over a range of voltages (±500 V) and their current collection and arcing characteristics were measured. In particular, the electron current collected by the so-called snap-over phenomena for positively biased solar arrays[77-79] was studied. Likewise, arcing for large negative potentials were also monitored[75,76]. The PASP Plus results[80] demonstrated that arcing levels were indeed strongly dependent on bias voltage.

The second low altitude charging experiments of interest are those associated with the Ballistic Missile Defense Organization's Space Power Experiment Aboard Rockets (SPEAR) Program[81]. In a series of three launches between 1987 and 1993, rockets were used to characterize the ability of a power system to maintain high voltages (upwards of 40 kV) in a dense ionospheric plasma (~200 to 300 km). These rocket flights were very successful in demonstrating the generation and control of multi-kV potentials in dense, ionospheric plasma. Careful, ground-based studies permitted accurate modeling of the subsequent observations and detailed evaluations of a variety of techniques for controlling, measuring, and establishing high potentials in space without the need for heavy insulation relative to the plasma. In particular, SPEAR III, successfully launched on March 15, 1993, completed a comprehensive test of methods for grounding high voltages in space (hollow cathodes, field emission, heated filaments, and neutral gas releases)[81-84]. These results promise a new era in the utilization of high voltage systems in space.

A final issue to be considered is the application of these results to the International Space Station. The major issues associated with the International Space Station are its huge size and solar arrays. In addition to the preceding, various modeling efforts have attempted to address each of these features explicitly. For example, the floating potential and wake structure of the International Space Station and the likelihood of arcing have been extensively addressed by Hastings, Wang, and others[45,85]. Plasma contactors in particular have been shown to play an important role in current collection and controlling floating potentials on the International Space Station's solar arrays and in limiting sputtering and arcing. These papers, however, represent only a small portion of the plasma and charging studies that will ultimately come from our utilization of the International Space Station in the years ahead—the reader is referred to the two sessions to be held at this conference for the latest, in-situ studies of the International Space Station high voltage interactions.

Conclusions

To summarize, the study and analysis of spacecraft charging over the last 20 years has demonstrated a growing maturity. Surface charging continues to be recognized as a serious operational threat to spacecraft and useful design guidelines are in place for its mitigation that were made possible in large part by the success of the SCATHA program. Internal charging has grown noticeably more important as a source of anomalies due to charging/arcing. With the flight of CRRES and its internal charging experiment, flight confirmation now exists of this phenomenon over the entire radiation belts. A formal internal charging design guideline was recently completed. Low altitude charging effects are slowly yielding to detailed computer analysis and experiment. Theory and evidence are converging on consistent models and techniques--successful conclusion of this process promises major advances in the utilization of the low altitude space environment. In particular, the use of tethers and of high voltage systems now appear possible if proper consideration is given to the details of the processes involved. For the future, there are, however, still many challenges. For example, the so-called "critical ionization velocity" phenomenon proposed by Alfven[86] remains an intriguing issue for low altitude plasma interactions[87]. The International Space Station itself promises to be a fertile laboratory setting for studying this and many other unusual plasma/charging interactions. Finally, there will be new areas that need to be investigated such as "dusty plasmas"[88] or the fields associated with truly large structures such as the proposed multi-kilometer solar sails. Even so, the last twenty years has seen significant and meaningful progress in an important scientific and engineering area of research--spacecraft charging.

Acknowledgments

This work was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The Internal Charging Handbook can be obtained on-line at http://standards.jpl.nasa.gov/jpl-nasa. The Surface Charging Handbook, NASA 2361, can be obtained in pdf format on-line at http://powerweb.grc.nasa.gov/pvsee/publications/geoguide.pdf

CL 97-67

References

[1]Cooke, D., "6th Spacecraft Charging Technology Conference," AF Research Laboratory, Hanscom AFB, MA, 1998.

[2]Hilgers, A., "7th Spacecraft Charging Technology Conference, 2001:A Spacecraft Charging Odyssey," Noordwijk, The Netherlands, European Space AGency, SP-476, 2001.

[3]Hastings, D.E., "A Review of Plasma Interactions with Spacecraft in Low Earth Orbit," *J. Geophys. Res.*, Vol. 100, No. A8, August, 1995, pp. 14,457-14,483.

[4]Garrett, H.B., and A.C. Whittlesey, "Spacecraft Charging, an Update," *IEEE Trans. on Plasma Phys.*, Vol. Special Issue on Space Plasmas, Vol. 28, No. 6, No. Decmber, 2000a, pp. 2017-2028.

[5]Garrett, H.B., and C.P. Pike, ed. *Space Systems and Their Interactions with Earth's Space Environment.* Prog. Astronaut. Aeronaut.,Series Editor M. Summerfield, Vol. 71, American Institute of Aeronautics and Astronautics, New York, NY, 1980, 737.

[6]Tribble, A., *The Space Environment: Implications for Spacecraft Design*, Princeton University Press, Princeton, NJ, 1995.

[7]Hastings, D., and H.B. Garrett, *Spacecraft-Environment Interactions*, 1st ed. Atmospheric and Space Science Series, ed. A.J. Dessler, Cambridge University Press, Cambridge, England, 1996, 292.

[8]Koons, H.C., *et al.*, "The Impact of the Space Environment on Space Systems," Rpt. No. TR-99(1670)-1, Aerospace Corp., 1999.

[9]Lai, S.T., "A Survey of Spacecraft Charging Events," *AIAA 36th Aerospace Sciences Meeting and Exhibit*, Reno NV, AIAA 88-1042, 1998.

[10]Feynman, J., and S. Gabriel, ed. *Interplanetary Particle Environment, Proceedings of a Conference.* JPL 88-28 ed. Vol. Jet Propulsion Laboratory, Pasadena, CA, 1988, 167.

[11]Whittlesey, A.C., "Avoiding Problems Caused by Spacecraft On-Orbit Internal Charging Effects," NASA-HDBK-4002, NASA, 1999.

[12]Divine, T.N., and H.B. Garrett, "Charged particle distributions in Jupiter's magnetosphere," *J. Geophys. Res.*, Vol. 88, No. A9, Sept., 1983, pp. 6889-6903.

[13]Garrett, H.B., and A. Hoffman, "Comparison of Spacecraft Charging Environments at the Earth, Jupiter, and Saturn," *IEEE Trans. on Plasma Phys.*, Vol. Special Issue on Space Plasmas, Vol. 28, No. 6, No. December, 2000b, pp. 2048-2057.

[14]Khurana, K.K., M.G. Kivelson, T.P. Armstrong, and R.J. Walker, "Voids in Jovian Magnetosphere Revisted: Evidence of Spacecraft Charging," *J. Geophys. Res.*, Vol. 92, No. A12, 1987, pp. 13,399-13,408.

[15]Bridge, H.S., *et al.*, "Plasma Observations Near Uranus: Initial Results from Voyager 2," *Science*, Vol. 233, No. July, 1986, pp. 89-93.

[16]Purvis, C.K., H.B. Garrett, A.C. Whittlesey, and N.J. Stevens, "Design Guidelines for Assessing and

Controlling Spacecraft Charging Effects," NASA TP-2361, NASA, 1984.

[17]Anon., "Electromagnetic Compatibility Requirements for Space Systems," MIL-STD 1541A, United States Air Force, U.S. Government Printing Office, 1987.

[18]Koons, H.C., J.F. Mizera, J.F. Fennell, and D.F. Hall, "Spacecraft Charging--Results from the SCATHA Satellite," *Astronautics and Aeronautics,* 1981, pp. 44-47 .

[19]Fennell, J.F., "Description of P78-2/SCATHA Satellite and Experiments," in *The IMS Source Book: Guide to the International Magnetospheric Study Data Analysis*American Geophysical Union, Washington, DC, 1982, pp. 65-81.

[20]Li, W.-W., and E.C. Whipple, "A Study of SCATHA Eclipse Charging," *J. Geophys. Res.*, Vol. 93, No. A9, September 1, 1988, pp. 10041-10046.

[21]Arnoldy, R.L., "Signature in the Interplanetary Medium for Substorms," *J. Geophys. Res.*, Vol. 76, No. 22, August 1, 1971, pp. 5189-5201.

[22]Foster, J.C., D.H. Fairfield, K.W. Ogilvie, and T.J. Rosenberg, "Relationship of Interplanetary Parameters and Occurrence of Magnetospheric Substorms," *J. Geophys. Res.*, Vol. 76, No. 28, October 1, 1971, pp. 6971-6975.

[23]Feynman, J., and S.B. Gabriel, "On Space Weather Consequences and Predictions," *J. Geophys. Res.*, Vol. 105, No. A5, May 1, 2000, pp. 10,543-10,564.

[24]Garrett, H.B., A.G. Rubin, and C.P. Pike, "Prediction of Spacecraft Potentials at Geosynchronous Orbit," *Solar-Terrestrial Prediction Proceedings, Vol. II*, Boulder, CO, NOAA Environmental Research Laboratories, 1979.

[25]Lam, H.-L., and J. Hruska, "Magnetic Signatures for Satellite Anomalies," *J. Spacecraft*, Vol. 28, No. 1, Jan-Feb, 1991, pp. 93-99.

[26]Mandell, M.J., P.R. Stannard, and I. Katz, "NASCAP Programmer's Reference Manual," Rep. SSS-84-6638, S-Cubed, La Jolla, CA, 1984.

[27]Garrett, H.B., D.C. Schwank, P.R. Higbie, and D.N. Baker, "Comparison Between the 30-80 keV Electron Channels on ATS-6 and 1976-059A During Conjunction and Application to Spacecraft Charging Prediction," *J. Geophys. Res.*, Vol. 85, 1980, pp. 1155-1162.

[28]Wilkinson, D.C., "National Oceanic and Atmospheric Administration's Spacecraft Anomaly Data Base and Examples of Solar Activity Affecting Spacecraft," *J. Spacecraft*, Vol. 31, No. 2, March-April, 1994, pp. 160-165.

[29]Leach, R.D., and M.B. Alexander, ed. *Failures and Anomalies Attributed to Spacecraft Charging*. Vol. NASA Ref. Publ. 1375, National Aerounautics and Space Administration, 1995, .

[30]Lanzerotti, L.J., K. LaFleur, and C.G. Maclennan, "Geosynchronous Spacecraft Charging in January 1997," *Geophys. Res. Lttrs.*, Vol. 25, No. 15, August 1, 1998, pp. 2967-2970.

[31]Hoeber, C.F., E.A. Robertson, I. Katz, V.A. Davis, and D.B. Snyder, "Solar Array Augmented Electrostatic Discharge in GEO," *17th International Communications Satellite Systems Conference and Exhibit, Feb. 23-27*, Yokihama, Japan, American Institute of Aeronautics and Astronautics, AIAA 98-1401, 1998.

[32]Ferguson, D., "Solar Array Arcing in Plasmas," *Third Annual Workshop on Space Operations Automation and Robotics*, Houston, TX, July 25-27, 1989.

[33]Cho, M., and D.E. Hastings, "Dielectric Charging Processes and Arcing Rates of High-Voltage Solar Arrays," *J. Spacecraft*, Vol. 28, 1991, pp. 698.

[34]Snyder, D.B., D.C. Ferguson, B.V. Vayner, and J.T. Galofaro, "New Spacecraft-Charging Solar Array Failure Mechanism," *6th Spacecraft Charging Technology Conference*, Hanscom AFB, MA, AF Research Laboratory, Nov. 2-6, 1998.

[35]Katz, I., V.A. Davis, and D.B. Snyder, "Mitigation Techniques for Spacecraft Charging Induced Arcing on Solar Arrays," *36th Aerospace Sciences Meeting and Exhibit, January 11-14*, Reno, NV, American Institute of Aeronautics and Astronautics, AIAA 99-0215, 1999.

[36]Leung, P., A.C. Whittlesey, H.B. Garrett, P.A. Robinson Jr., and T.N. Divine, "Environment-Induced Electrostatic Discharges as the Cause of Voyager 1 Power-On Resets," *J. Spacecraft*, Vol. 23, No. 3, May/June, 1986, pp. 323-330.

[37]Whittlesey, A.C., and P. Leung, "Space Plasma Charging--Lessons from Voyager," *AIAA 25th Aerospace Sciences Meeting, January 12-15*, Reno, NV, 1987.

[38]Sorensen, J., "An Engineering Specification of Internal Charging," *ESA Symposium Proceedings on "Environment Modeling for Space-Based Applications"*, Noordwijk, NL, European Space Agency, SP-392, 18-20 September, 1996.

[39]Koons, H.C., and M.W. Chen, "An Update on the Statistical Analysis of MILSTAR Processor Upsets," *Government Microcircuit Applications Conference*, Monterey CA, GOMAC, XXIV, 1999.

[40]Fennell, J.F., H.C. Koons, and J.B. Blake, "A Deep Dielectric Charging Environmental Specification for Geosynchronous and HEO/Molniya Satellites," *Government Microcircuit Applications Conference*, Monterey CA, GOMAC, XXIV, 1999.

[41]Frederickson, A.R., "Quantitative Guidelines for Charged Spacecraft Derived from the Physics of Discharges," *Government Microcircuit Applications Conference*, Monterey CA, GOMAC, XXIV, 1999.

[42]Frederickson, A.R., "Upsets Related to Spacecraft Charging," *IEEE Trans. on Nuc. Sci.*, Vol. 43, No. 2, 1996, pp. 426-441.

[43]Frederickson, A.R., "New Scaling Laws for Spacecraft Discharge Pulses," *7th Spacecraft Charging Technology Conference, 2001:A Spacecraft Charging Odyssey*, Noordwijk, The Netherlands, European Space AGency, SP-476, 2001.

[44]Stone, N.H., "The Aerodynamics of Bodies in a Rarefied Ionized Gas with Applications to Spacecraft Environmental Dynamics," NASA TP-1933, NASA Marshall Space Flight Center, 1981.

[45]Wang, J., P. Leung, H. Garrett, and P. Murphy, "Multibody-Plasma Interactions: Charging in the Wake," *J. Spacecraft*, Vol. 31, No. 5, September-October, 1994, pp. 889-894.

[46]Enloe, C.I., D.L. Cooke, S. Meassick, C. Chan, and M.F. Tautz, "Ion Collection in a Spacecraft Wake: Laboratory Simulations," *J. Geophys. Res.*, Vol. 98, 1993, pp. 13,635-13,644.

[47]Enloe, C.I., *et al.*, "The Charging Hazards and Wake Studies (CHAWS) Experiment," American Institute of Aeronautics and Astronautics, New York, NY, AIAA 95-00892, 1995.

[48]Enloe, C.L., *et al.*, "High-Voltage Interactions in Plasma Wakes: Results from the Charging Hazards and Wake Studies (CHAWS) Flight Experiments," *J. Geophys. Res.*, Vol. 102, No. A1, January 1, 1997, pp. 425-433.

[49]Lilley, J.R., Jr., D.L. Cooke, G.A. Jongeward, and I. Katz, "POLAR User's Manual," GL-TR-89-0307, AF Geophysics Laboratory, Hanscom AFB, MA, 1989.

[50]Mandell, M.J., and V.A. Davis, "User's Guide to NASCAP/LEO," SSS-R-8507300-R2, NASA Lewis Research Center, Cleveland, OH, 1990.

[51]Davis, V.A., M.J. Mandell, D.L. Cooke, and C.L. Enloe, "High-Voltage Interactions in Plasma Wakes: Simulation and Flight Measurements from the Charge Hazards and Wake Studies (CHAWS) Experiment," *J. Geophys. Res.*, Vol. 104, No. A6, June 1, 1999, pp. 12,445-12,459.

[52]Hastings, D.E., and R. Samanta Roy, "A Brief Overview of Electrodynamic Tethers," in *The Behavior of Systems in the Space Environment,* R.N. DeWitt, D.P. Duston, andA.K. Hyder, Editors, Kluwer Academic Publishers, Dordrecht, The Netherlands, 1993, pp. 825-835.

[53]Dobrownoly, M., and E. Melchioni, "Electrodynamic aspects of the first tethered satelllite mission," *J. Geophys. Res.*, Vol. 98, 1993, pp. 13761-13778.

[54]Oberhardt, M.D., D.A. Hardy, I. katz, M.P. Gough, and D.C. Thompson, "Vehicle charging as measured by the shuttle potential and return electron experiment aboard TSS-1," Rep. AIAA 93-0699, American Institute of Aeronautics and Astronautics, 1993.

[55]Aguero, V.M., *et al.*, "Current Collection Model Characterizing Shuttle Charging During the Tethered Satellite System Missions," *J. Spacecraft*, Vol. 37(2), No. Mar-Apr, 2000, pp. 212-217.

[56]Nobles, W., "Electrodynamic Tethers for Energy Conversion," *NASA/AIAA/PSN International Converence on Tethers in Space, 17-19 September*, Arlington, VA, 1986.

[57]Vignoli, M., M. Miller, and M. Matteoni, "Power Generation with Electrodynamic Tethers," *NASA/AIAA/PSN International Conference on Tethers in Space*, Arlington, VA, 17-19 September, 1986.

[58]Johnson, L., *et al.*, "Electrodynamic Tethers for Spacecraft Propulsion," *36th Aerospace Sciences Meeting and Exhibit*, Reno, NV, American Institute of Aeronautics and Astronautics, Reston, VA, AIAA 98-0983, 1998.

[59]Vas, I.E., "Space Station Reboost with Electrodynamic Tethers," *J. Spacecraft*, Vol. 37(2), No. Mar-Apr, 2000, pp. 153.

[60]Estes, R.D., J. Sanmartin, and M. Martinez-Sanchez, "Performance of Bare-Tether Systems Under Varying Magnetic and Plasma Conditions," *J. Spacecraft*, Vol. 37(2), No. Mar-Apr, 2000, pp. 197-204.

[61]Gilchrist, B.E., and S.G. Bilen, "Simulated Bare Electrodynamic Tethers in a Dense, Flowing, High-Speed Plasma," *Eleventh Annual NASA-JPL-MSFC Advanced Space Propulsion Research Workshop*, Pasadena, CA, Jet Propulsion Laboratory, 2000.

[62]Lilley, J.R., *et al.*, "Comparison of the Theoretical Calculations with Plasma Motor Generator (pmg) Experimental Data," Rep AIAA 94-0328, American Institue of Aeronautics and Astronautics, Reston, VA, 1994.

[63]Gabriel, S.B., R.M. Jones, and H.B. Garrett, "Alfven Propulsion at Jupiter," *Second International Conference on Tethers in Space*, Venice, Italy, October 7, 1987.

[64]Gilchrist, B.E., *et al.*, "Enhanced Electrodynamic Tether Currents due to Electron Emission from a Neutral Gas Discharge: Results from the TSS-1R Mission," *Geophys. Res. Lett.*, Vol. 25, No. 4, 1998, pp. 445-448.

[65]Belcastro, V., P. Veltri, and M. Dobrownoly, "Radiation from long conducting tethers moving in the near-earth environment," *Nuovo Cimento*, Vol. 5, 1982, pp. 537-560.

[66]Barnett, A., and S. Olbert, "Radiation of Plasma Waves by a Conduction Body Moving through a Magnetized Plasma," *J. Geophys. Res.*, Vol. 91, 1986, pp. 10117-10135.

[67]Hastings, D.E., and J. Wang, "The Radiation Impedance of a Electrodynamic Tether with End Connectors," *Geophys. Res. Lett.*, Vol. 14, 1987, pp. 519-522.

[68]Donahue, D.J., T. Neubert, and P.M. Banks, "Estimated radiated power from a conducting tethered satellite system," *J Geophys. Res.*, Vol. 96, 1991, pp. 21245-21253.

[69]Urrutia, J.M., R.L. Stenzel, and C.L. Rousculp, "Three-Dimensional Currents of Electrodyamic Tethers Obtained from Laboratory Models," *Geophys. Res. Lttrs.*, Vol. 21, No. 6, March 15, 1994, pp. 413-416.

[70]Besse, A.L., A.G. Rubin, and D.A. Hardy, "Charging of DMSP/F6 in Aurora on 10 January 1983," *Proceedings of the Spacecraft Environmental Interactions Technology Conference-1983*, NASA CP-2359/AFGL-TP-85-0018, 1985.

[71]Gussenhoven, M.S., "High Level Spacecraft Charging in the Low Altitude Polar Auroral Environment," *J. Geophys. Res.*, Vol. 90, 1985, pp. 11009-11023.

[72]Anderson, P.C., and H.C. Koons, "Spacecraft Charging Anomaly on a Low-Altitude Satellite in an Aurora," *J. Spacecraft*, Vol. 33, No. 5, Sept., 1996.

[73]Cooke, D.L., "Simulation of an Auroral Charging Anomaly on the DMSP Satellite," *36th Aerospace Sciences Meeting and Exhibit*, Reno, NV, American Institute of Aeronautics and Astronautics, AIAA-98-0385, January 12-15, 1998.

[74]Sasaki, S., "Plasma Effects Driven by Electromotive Force of Spacecraft Solar Array," *Geophys. Res. Lttrs.*, Vol. 26, No. 3, July 1, 1999, pp. 1809-1812.

[75]Guidice, D., P. Severance, H. Curtis, and M. Piszczor, "Investigation of Space-Environment Effects on Photo-Voltaic Technologies by the PASP Plus Experiment1," *33rd Aerospace Sciences Meeting and Exhibit, January 9-12*, Reno, NV, AIAA 95-037, 1995.

[76]Guidice, D., and K. Ray, "PASP Plus Measurements of Space Plasma and Radiation Interactions on Solar Arrays," *34th Aerospace Sciences Meeting and Exhibit*, Reno, NV, American Institute of Aeronautics and Astronautics, AIAA 96-0926, 1996.

[77]Stevens, N.J., "Review of Interactions of Large Space Structures with the Environment," in *Space Systems and Their Interactions with Earth's Space Environment,* H.B. Garrett and C.P. Pike, Editors, AIAA Press, New York, NY, 1980d, pp. 437-454.

[78]Leung, P., "Discharge Characteristics of a Simulated Solar Array," *IEEE Trans. Nucl. Sci.*, Vol. NS-30, 1983, pp. 4311.

[79]Ferguson, D., G. Hillard, D. Snyder, and N. Grier, "The Inception of Snapover on Solar Arrays: A Visualization Technique," *36th Aerospace Sciences Meeting and Exhibit*, Reno, NV, American Institute of Aeronautics and Astronautics, AIAA-98-1045, 1998.

[80]Soldi, J.D., D.E. Hastings, D. Hardy, D. Guidice, and K. Ray, "Arc Rate Predictions and Flight Data Analysis for the PASP Plus Experiment," *34th Aerospace Sciences Meeting and Exhibit*, Reno, NV, American Institute of Aeronautics and Astronautics, AIAA 96-0368, 1996.

[81]Rustan, P., H.B. Garrett, and M.J. Schor, "High Voltages in Space, Innovation in Space Insulation," *IEEE Trans. Elec. Insulation*, Vol. 28, No. 5, October, 1993, pp. 855-865.

[82]Berg, G.A., *et al.*, "Overview of the Effects of Neutral Gas Releases on High-Voltage Sounding Rocket Platforms," *Adv. Space Res.*, Vol. 15(12), 1995, pp. 83.

[83]Siefring, C.L., and P. Rodriguez, "Results from the NRL Floating Probe on SPEAR III: High Time Resolution Measurements of Payload Potential," in *Measurement Techniques in Space Plasmas, Geophys. Monogr. Ser.,* R.F. Pfaff, J.E. Borovsky, and D.T. Young, Editors, American Geophysical Union, Washington, DC, 1998, pp. 223-228.

[84]Walker, D.N., *et al.*, "Discharging Spacecraft through Neutral Gas Release: Experiment and Theory," *J. Geophys. Res.*, Vol. 104, No. 6, June 1, 1999, pp. 12,473-12,485.

[85]Hastings, D.E., M. Cho, and J. Wang, "The Space Station Freedom Structure Floating Potential and the Probability of Arcing," *J. Spacecraft*, Vol. 29, 1992b, pp. 830-834.

[86]Alfven, H., *On the Origin of the Solar System*, Oxford University Press, New York, NY, 1954.

[87]Lai, S.T., and E. Murad, "Critical Ionization Velocity Experiments in Space," *Planet. Space Sci.*, Vol. 37, No. 7, 1989, pp. 865-872.

[88]Chutjian, A., "Recent Applications of Gaseous Dicharges: Dusty Plasmas and Upward-Directed Lightning," in *Advances in Atomic, Molecular and Optical Physics*Academic Press, New York, NY, 2000, pp. 373-398.